Influence of the pion-nucleon interaction on the collective pion flow in heavy ion reactions

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Abstract

We investigate the influence of the real part of the in-medium pion optical potential on the pion dynamics in intermediate energy heavy ion reactions at 1 GeV/A. For different models, i.e. a phenomenological model and the Δ–hole model, a pionic potential is extracted from the dispersion relation and used in Quantum Molecular Dynamics calculations. In addition with the inelastic scattering processes we thus take care of both, real and imaginary part of the pion optical potential. A strong influence of the real pionic potential on the pion in-plane flow is observed. In general such a potential has the tendency to reduce the anticorrelation of pion and nucleon flow in non-central collisions.

Keywords: Heavy ion reactions, QMD, pion production, pion in-plane flow, dispersion relation, pion optical potential.

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The pions strongly dominate the production of mesons in intermediate heavy ion collisions. Due to their strong interaction with the nuclear medium it is, however, still an open question if pions can serve as a sensitive probe of hot and compressed nuclear matter. The analysis of pion spectra [1, 2, 3] is supposed to provide information about the creation and dynamics of resonaces in compressed and excited nuclear matter. Besides the dominant $\Delta(1232)$ resonance high energetic pion spectra may also yield information about the role of higher resonances, e.g. the $N^*(1440)$ [4]. In addition there have been also measurements of collective pion observables, i.e. the in-plane pion flow has been measured by the DIOGENE group for the system Ne+Pb at 800 MeV/A [5] and the squeeze out, i.e. the flow perpendicular to the reaction plane, by, e.g., the TAPS collaboration [6].

Since the reaction dynamics are strongly influenced by the pionic channels of the NN inelastic collision processes the understanding of the pion dynamics is of particular interest. However, most theoretical transport calculations [7, 8] included the interaction of the pions with the surrounding nuclear medium only by collision processes, i.e. parametrizing the imaginary part of the pion optical potential. Such calculations are able to reproduce qualitatively, e.g., the DIOGENE data but as a general feature seem to underpredict the total amount of flow [7, 9]. Hence, we present here studies which also include the real part of the pion optical potential as a potential interaction for the pions during their propagation through the nuclear medium and thus we take care of the full in-medium pion optical potential.

The knowledge of the pion optical potential from elastic pion–nucleus scattering is, however, restricted to nuclear densities at and below saturation and relatively small energies [10]. In heavy ion reactions at intermediate energies from about 0.1 to 2 GeV/A baryon densities up to three times saturation density are reached and pion momenta of several hundred MeV can occure. In this range the real part of the pion potential is almost unknown. Thus, one has to extrapolate the pion dispersion relation to the ranges relevant for heavy ion collisions. To obtain an estimation of such in-medium effects we apply two models, i.e. the Δ–hole model [11, 12] and a

phenomenological ansatz suggested by Gale and Kapusta [13]. The application of these models allows to investigate the influence of the possible boundary cases, i.e. a soft (Δ–hole) and a rather strong phenomenological potential, and to demonstrate the influence on pionic observable in heavy ion collisions, in particular on the pion in-plane transverse flow produced in non-central collisions.

The dynamics of the nucleus-nucleus collision are simulated within the framework of Quantum Molecular Dynamics (QMD) and a soft momentum dependent Skyrme force is used for the nuclear mean field. A detailed description of the QMD approach can be found in Refs. [14, 15]. We included the $\Delta(1232)$ and the $N^*(1440)$ baryonic resonances which as well as the pions originating from their decay are explicitely treated, i.e. in a non-pertubative way. For the cross sections of the inelastic channels ($NN \rightarrow N(\Delta, N^*)$) and for the lifetimes of the resonances we use parametrizations determined from one-boson-exchange amplitudes in Born approximation [16]. For the decay of the N^* and Δ following decay channels are taken into account: One pion decay ($\Delta, N^* \rightarrow N + \pi$), two pion decay ($N^* \rightarrow N + 2\pi$) and the decay of the N^*-resonance in a Δ-resonance and a pion ($N^* \rightarrow \Delta + \pi$). These processes are calculated with energy dependent decay probabilities as given in Ref. [16]. In all collision processes a medium dependence is included via the Pauli blocking of the final states according to the phase space occupancy. Furthermore, the momentum dependence of the nuclear mean field results in a (non-relativistic) effective mass of the baryons. Thus we are able to reasonably reproduce the total pion multiplicities, however, overestimate them by about 20% which seems to be a common feature of present transport calculations [8]. This fact is supposed to be due to the description of the resonance rescattering channel ($N(\Delta, N^*) \rightarrow NN$) by a detailed balance argument which leads to an underestimation of this process [7]. The multiplicities itself are found to be nearly unaffected by the real pionic potential. On the other handside, the pionic flow per particle does not react on slight changes in the multiplicities.

The pions are propagated between their collisions with the nucleons under consideration of the interaction with the surrounding nuclear matter. The interaction

of the pions with surrounding nuclear matter results in a pion self energy Π entering into the in-medium pion dispersion relation

$$\omega(\mathbf{q})^2 = \mathbf{q}^2 + m_\pi^2 + \Pi(\omega, \mathbf{q}, \rho) \quad . \tag{1}$$

Here the self energy depends on the energy ω and the momentum $\mathbf{q}$ of the pion and on the nuclear matter density ρ. In the framework of the Δ-hole model the self energy is finally given in the following form

$$\Pi(\omega, \mathbf{q}, \rho) = \frac{\mathbf{q}^2 \chi(\omega, \mathbf{q}, \rho)}{1 - g' \chi(\omega, \mathbf{q}, \rho)} \tag{2}$$

with

$$\begin{aligned} \chi(\omega, \mathbf{q}, \rho) &= -\frac{8}{9} \left(\frac{f_\Delta}{m_\pi} \right) \rho \frac{\omega_\Delta(\mathbf{q})}{\omega_\Delta^2(\mathbf{q}) - \omega^2} \\ \omega_\Delta &= \sqrt{M_\Delta^2 + \mathbf{q}^2} - M_N \quad . \end{aligned}$$

The parameters entering into Eq. (2), in particular the $\pi N \Delta$ coupling constant f_Δ and the correlation parameter g' are taken in consistence with the OBE parameters of Ref. [16] and a consistent treatment of the real and imaginary part of the pion optical potential is achieved.

The self energy obtained from the Δ-hole model, Eq. (2), includes beside of excitation of ΔN^{-1} states also short range correlations of these states. In this approximation one neglects, however, terms of higher order [17] which are necessary to prevent the system to undergo a phase transition to the so called pion condensation. Although this approach works reasonable at low baryon densities and low pion momenta [12] it yields the wrong boundary conditions when the pion passes through the surface of the nuclear matter into the vacuum. A possibility to avoid these unphysical features is to mix the two solutions of the dispersion relation, Eq. (1), i.e. the pion-like and the Δ-hole-like branch in a way that the physical boundary conditions are fulfilled [4]. Proceeding this way pion condensation only takes place at unphysically high densities. However, such a construction leads to a strong softening

of the in-medium effects and hence one can't be sure that the modified dispersion relation still represents the true pion-nucleon interaction.

To improve on this we also consider the phenemenological ansatz of Gale and Kapusta [13] which is motivated by the results of low-energy pion-nucleus scattering and the observation of pionic atoms. The pion dispersion relation reads

$$\omega(q) = \sqrt{(|\mathbf{q}| - q_0)^2 + m_0^2} - U \tag{3}$$

$$\begin{aligned} \text{with} \quad U &= \sqrt{q_0^2 + m_0^2} - m_\pi \\ m_0 &= m_\pi + 6.5(1 - x^{10}) m_\pi \\ q_0^2 &= (1-x)^2 m_\pi^2 + 2 m_0 m_\pi (1-x) \quad . \end{aligned} \tag{4}$$

Here a phenomenological medium dependence is introduced via $x = e^{-a(\rho/\rho_0)}$ with the parameter $a = 0.154$ which allows to extrapolate to higher densities thereby avoiding the appearence of pion condensation.

Fig. 1 shows the pion dispersion relation for two representative densities obtained by the two approaches. It becomes obvious that the phenemenological dispersion relation given by Eq. (3) yields a strong attractive pion-nucleus optical potential (Pot.2) in comparison to the Δ-hole model (Pot.1). In contrast to Pot.2 the medium dependence of Pot.1 is relatively weak. Hence, the application of the two potentials allows to estimate the magnitude of such effects.

In Fig.2 the π^- energy spectra for a central (b$\leq$2.8 fm) La+La reaction at 1.35 GeV/A are compared to the BEVELAC data of Ref. [18]. It is seen that for low energies the agreement with the experiment is generally improved by the inclusion of a pionic potential which, due to its attraction, lowers the kinetic energy of the pions. With increasing energy this behavior becomes more complex. The weak Pot.1 is still in a reasonable agreement with the data. In the case of Pot.2 the attraction is, however, so pronounced that the pions are forced to follow the trajectories of the nucleons resulting in an enforcement of the high energy components of the spectrum. Since the high energy tails of, e.g., p_t-spectra measured by the TAPS collaboration [2] are systematically underestimated by conventional calculations [8] the inclusion

of a pionic potential may help to resolve on this problem.

A quantity of particular interest is the pion transverse flow. In previous studies an anticorrelation of the pion and the nucleon transverse flow has been predicted for non-central collisions [8]. New results of the FOPI Collaboration seem to confirm this observation [19]. Such an anticorrelation which in part has also been observed by the DIOGENE group is explained by a shadowing effect due to the absorption and rescattering of the pions by spectator nucleons. Due to the large asymmetry of the considered system the DIOGENE data are, however, strongly distorted by the participant-spectator geometry and no definit (anti)correlation has been observed over the entire rapidity range of the reactions. The magnitude of this shodowing effect grows with the number and the flow of the spectator nucleons, i.e. it is proportional to the impact parameter. This can be seen from Fig.3 where the directed transverse momentum $p_x^{dir} = \frac{1}{N}\sum_i sign(Y_{CM}^i)p_x^i$ is shown as a function of the impact parameter for the system Ca+Ca at 1 GeV/A. The negative directed flow in non-central collisions indicates the anticorrelation with the positive directed flow of the nucleons. It is further seen that the attractive potential interaction in general has the tendency to reduce this anticorrelation and a strong potential like Pot.2 can even convert it into a correlation.

This behaviour can be explained as follows: the real part of the pion optical potential leads to a bending of the trajectories of the pions in the direction where the majority of the nucleons moves. The two effects, i.e. the potential and the shadowing effect, counterbalance each other and hence, if the pion-nucleus potential is strong enough one observes even a correlated pion flow.

Annother question of interest is the influence of the nuclear equation of state (EOS) on the pion flow. The previous results have been obtained with a momentum dependent Skyrme force [15] corresponding to a soft EOS. Fig.4 compares to the pion in-plane flow obtained with a momentum independent soft Skyrme and a momentum dependent hard Skyrme force. It turns out that the pion in-plane flow does not react very sensitiv on the nuclear EOS compared to the strong influence of the pion optical

potential and attempts to fix the EOS from there as suggested, e.g., in Ref. [8] will remain ambigous as long as these effects are not taken into account properly.

We conclude that the effect of the pion-nucleus optical potential extracted from the in-medium pion dispersion relation is of essential importance for the pion transverse flow. The dependence on the nuclear EOS is relatively small. This fact opens the possibilty to extract some information about the structure of the pion dispersion relation, in particular for its unknown ranges, from the pion flow in heavy ion collisions. However, in our opinion no final conclusions can be drawn from the present pion flow data. To obtain quantitative statements more refined measurements are necessary, in particular a detailed analysis of forthcoming results from the FOPI collaboration may help to clarify this situation.

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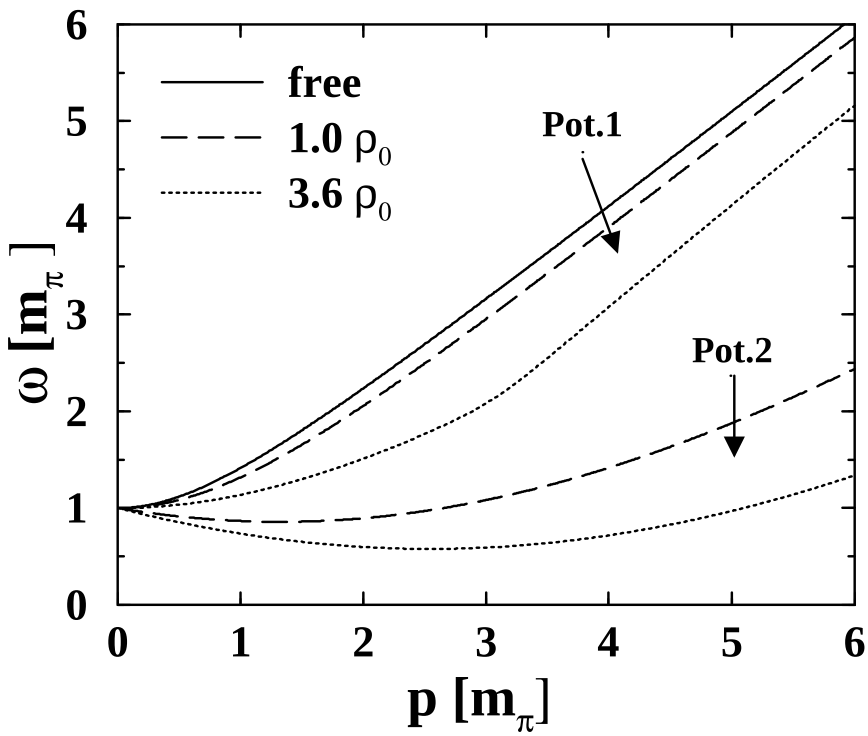

Figure 1: Comparison of the pion in-medium dispersion relations obtained within the Δ-hole model (Pot.1) and with the phenomenological ansatz according to Ref. [13] (Pot.2).

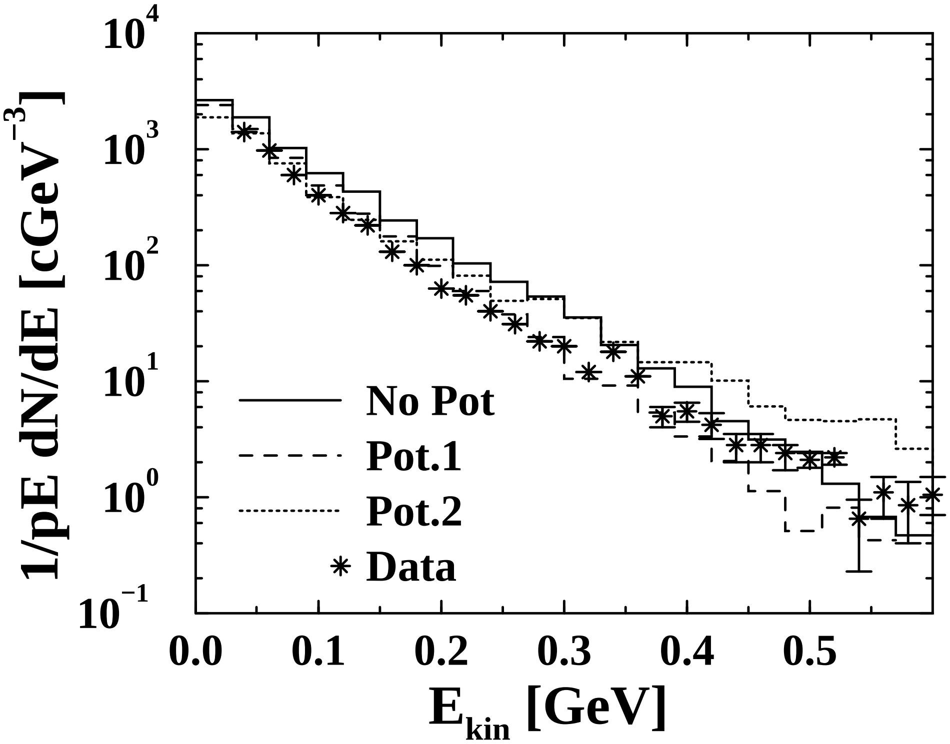

Figure 2: Comparison of π^- energy spectra for a central ($b \leq 2.8$fm) La+La reaction at 1.35 GeV/A. The calculations have been performed with and without the real part of the pion-nucleus optical potential. The data are taken from Ref. [18] and an angular cut of $60° \leq \Theta_{CM} \leq 120°$ has been applied.

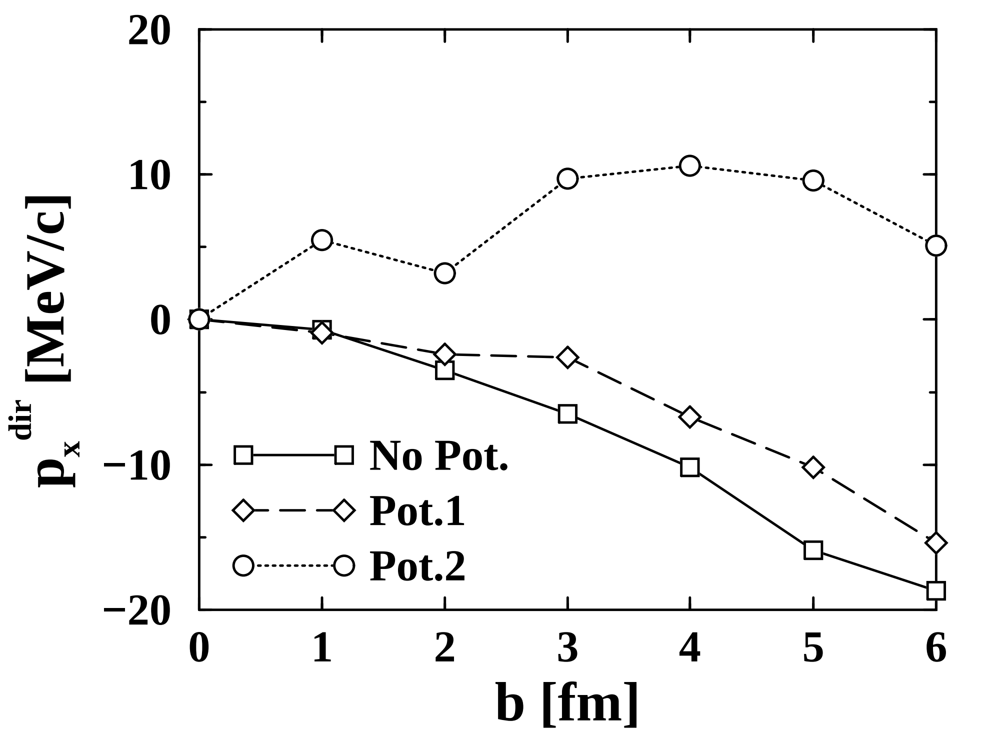

Figure 3: Directed pion flow p_x^{dir} as a function of the impact parameter with and without the real part of the pion-nucleus optical potential for the system Ca+Ca at 1 GeV/A.

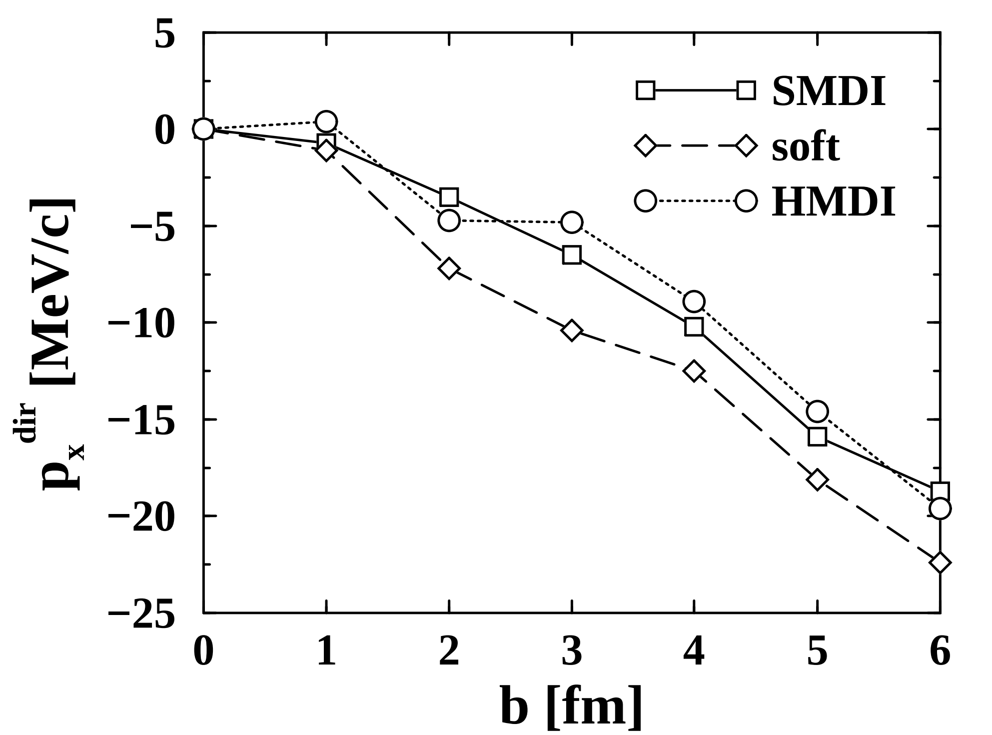

Figure 4: Dependence of the directed pion flow p_x^{dir} as a function of the impact parameter on the nuclear equation of state. The calculations are performed for the same system as in Fig.3 using a soft/hard momentum dependent Skyrme force (SMDI/HMDI) and a soft Skyrme force without momentum dependence (dashed line). In these calculations the real part of the pion optical potential has not been taken into account.